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Contract No. Nonr-1675(00)

DUCTED PROPELLER ASSAULT TRANSPORT

Survey – State of the Art

Report No. D181-945-003

15 May 1956

BELL Aircraft CORP.

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By direction of
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BELL Aircraft CORPORATION
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REPORT NO. D181-945-003 **MODEL**

Ducted Propeller Assault Transport Study

Survey of the State of the Art

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FOREWARD

Contract Nonr 1675 (00) was awarded to Bell Aircraft Corporation by the Office of Naval Research under sponsorship of the Army Transportation Corps. This is one of a series of five study contracts let to investigate the application of various schemes to the design of Vertical Take-off and Landing (VTOL) or Short Take-off (STO) Assault Transport Aircraft.

The particular field of investigation at Bell Aircraft is the application of ducted propeller propulsion systems to the design of aircraft capable of performing the Assault Transport mission. The results of the investigation are presented in the following listed reports:

TITLE	REPORT NUMBER
Summary Report	D181-945-001
Design Report	D181-945-002
Survey of the State of the Art	D181-945-003
Performance	D181-945-004
Stability and Control	D181-945-005
Duct and Propeller Analysis	D181-945-006
Preliminary Structural Analysis	D181-945-007
Standard Aircraft Characteristics Charts	D181-945-008

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Date: 7/30/56

By direction of
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Abstract

A review of the literature and conferences with interested agencies, bearing on the theory and design of ducted propellers were completed as part of the Navy Contract Nonr-1675(00) "A Study of Vertical Take Off and Landing Ducted Propeller Assault Transport Aircraft". The literature review is divided into two main groups which treat the problem from the viewpoint of classical propeller analysis and as compressors. Since the distinction is not always clear cut there is necessarily some overlap in the division. The results of conferences with the various interested agencies is contained in a third section.

TABLE OF CONTENTS

Summary and Conclusion

This report summarizes a survey of the "State of the Art" of ducted propeller design, theory, and experiment. In all, about 200 reports were reviewed of which about 75 were abstracted and included in this summary. Conferences were held with various agencies and companies to further extend the review. Reports of these conferences are included here.

The review of literature showed that while serious thought was given to ducted propellers during World War II, the advent of jet propulsion cut most of the work short with the result that very little experimental data was available. Of the 75 reports abstracted only 17 dealt directly with ducted propellers and of these only 8 contained experimental data. For the most part this data was the first step in investigating a new idea. That is, the tests covered a limited range of variables and were, in general, sufficient to show the desirability of a complete program. The majority of the reports concern fans and compressors, and the methods are often applicable to ducted propeller work. A general breakdown of the literature reviewed might be made as follows. In a group which was considered as treating the subject from the standpoint of incompressible flow and classical propeller analysis there were 44 reports. Twenty of these contained experimental data. The subjects covered were: wind tunnel fans 9, conventional propellers 3, ducts 13, ducted propellers 17, and isolated airfoils 3. A second grouping was made which dealt with compressors and treated the flow as compressible. There were 29 reports in this group of which 19 were experimental. The data of many of these reports was applicable to ducted propeller work, and were used in the ducted propeller design study carried out under this contract. While the available data was

sufficient to form the basis of a design study to establish feasibility, there exists a need for systematic experimental data for use in detail design.

The conferences on ducted propellers added substantially to the total information. Visits were made to the NACA at Langley Field, Virginia, and Cleveland, Ohio, to the Air Force Propeller Laboratory at Wright Field, Dayton, Ohio, to the University of Wichita in Kansas, to the Navy facility, the David Taylor Model Basin, Washington, D.C., to Princeton University in New Jersey, to Kaman Aircraft Corporation, Bloomfield, Connecticut, to Hamilton Standard Division of United Aircraft, Hartford, Connecticut, to Collins Radio Company, Cedar Rapids, Iowa.

The material compiled in this report forms a background of currently available information on ducted propellers. As a result of the need for more experimental data on ducted propellers, the Air Branch of the Office of Naval Research granted permission to the University of Wichita to redirect its effort under Contract Nonr-201(01) to obtain some experimental data in support of Bell Aircraft's ducted propeller study. At present two ducted propeller models designed by Bell are being prepared for test in the 7 by 10 foot tunnel at the University. At the same time the Navy facility at the David Taylor Model Basin initiated a fundamental experimental program on ducted propellers. These tests should be the start of an experimental program to supply the systematic data required for the future design of these propulsion units.

Bibliography

In compiling this bibliography pertinent to the design of ducted propellers some 200 reports were reviewed. Of these about 75 were abstracted and are presented in this section. Three text books are also included without abstracts.

The presentation of these abstracts is made under two major headings. The first section contains the reports which treat the problem from the viewpoint of incompressible flow and classical propeller blade element analysis. Included in this section are reports on ducts alone, ducted propellers, isolated airfoils, and lightly loaded fans. The second major section of the bibliography contains the reports which treat the problem from the viewpoint of compressor theory and practice. This group includes reports on compressors, on airfoils in cascade, and on the flow problems related to compressor design. Each of the major sections was subdivided into a section of theoretical reports and a section of reports containing experimental data. Within each subsection the reports are listed alphabetically by author.

Books

Keller, C. and Marks, L. S. "The Theory and Performance of Axial Flow Fans" McGraw-Hill New York 1937

Küchemann, D. and Weber, J. "Aerodynamics of Propulsion" McGraw-Hill New York 1953

Stepanoff, A. J. "Turboblowers, Theory, Design, and Application of Centrifugal and Axial Flow Compressors and Fans" John Wiley and Sons, New York 1955

IA Classical Propeller Blade Element Analysis and Incompressible Flow Analysis - Theory.

This section contains the abstracts of 24 reports. The subjects treated are: ducts, ducted propellers, bare propellers, and wind tunnel fans.

Betz, Albert: "THE THEORY OF CONTRA-VANES APPLIED TO THE PROPELLER." NACA TM909 September 1939

The optimum circulation distribution and hence the maximum theoretical thrust obtainable for contra-vanes fitted behind propellers is markedly dependent on the number of guide vanes. A theoretical development taking into account hub diameter, vane drag, and vane radius.

Corson, B. W., Jr.: "THE AERODYNAMICS OF A WIND TUNNEL FAN." NACA TN820, August 1941

The vortex blade-element theory modified to apply to an axial flow fan working in a duct is reviewed. Parameters are developed for use in the design of a fan and methods are developed for analyzing a fan of known design.

Crawford, W. R.: "THEORY OF SCREW FANS" No. I and No. II, The Engineer, Vol 70, P 150 September 6, 1940, and P 166 September 13, 1940

This report presents a basic treatment of screw fans. Equations for thrust and torque are presented in incompressible form. A method of blade element analysis based on 2 dimensional airfoil theory is also presented.

Küchemann, D. and Weber, J.: "THEORY OF THIN COWLINGS", Great Britain Ministry of Supply Reports and Translations, No. 989

Methods of calculating cooling flow and pressures and forces on cooling ducts.

Küchemann, D.: "CONCERNING THE FLOW ABOUT RING SHAPED COWLING OF FINITE THICKNESS - PART I" NACA TM1325, January 1952

The first step in setting up, by method of singularities, the flow conditions through axially symmetric ducts of finite thickness. In this report no attempt is made to find the singularity distribution for a particular duct; instead the ring source and sink are chosen and the resulting duct found. Examples showing the pressure and velocity distributions about several annular bodies with and without hub bodies are included.

Küchemann, D. & Weber, J. : "CONCERNING THE FLOW ABOUT RING-SHAPED COWLINGS, PART II - ANNULAR BODIES OF INFINITE LENGTH WITH CIRCULATION FOR SMOOTH ENTRANCE." NACA TM1326, November 1951

A treatment of annular bodies of infinite length, with circulation caused by distributing vortex rings of constant density over a stream surface extending to infinity. The influence of hub bodies is dealt with.

Küchemann, D. & Weber, J.: "ON THE FLOW AROUND RING-SHAPED COWLINGS, PART III - THIN RING PROFILES", Translated by McDonnell Aircraft Corporation, Department H GT-19, February 8, 1946

A theory of thin ring-shaped airfoils is given, which includes a simple approximation process for small circulations, corresponding to the theory of thin plane airfoils, and also a numerical method for large circulations.

Küchemann, D. & Weber, J.: "CONCERNING THE FLOW ABOUT RING-SHAPED COWLINGS PART XII - TWO NEW CLASSES OF CIRCULAR COWLS", NACA TM1360, October 1953

Cowlings specially designed for radiators, by the methods of the previous reports.

Küchemann, D.: "CONCERNING THE FLOW ON RING-SHAPED COWLINGS, PART XIII - THE INFLUENCE OF A PROJECTING HUB", NACA TM1361, October 1953

The influence of thickness and length of a hub projecting from an inlet opening was investigated on one of the two new classes of circular cowls, reported in NACA TM1360.

Lerbs, H. W.: "THEORETICAL CONSIDERATIONS ON SHROUDED PROPELLERS", David Taylor Model Basin Report C-543, June 1953

The flow and the forces which are generated by a propulsion system consisting of rotor, shroud and guide vanes are analyzed. For this purpose, the components of the system are replaced by proper singularities. From the component velocity fields and from the characteristic constants of the singularities, the interaction forces between the components are determined from which the net forces of the unit follow. The deduced expressions for thrust and power input taken together with pressure increase at the rotor, which arises from the action of the shroud, and with the condition of cavitation free flow form the basis for a method of design of a propulsion unit. To apply this method, knowledge of both lift versus angle of attack curves and of pressure distribution curves of sections in cascade is necessary.

Comparison of experimental results for the efficiency and for the interaction force between rotor and shroud are in fair agreement with the respective analytical expressions taking into account the lack of knowledge relative to the drag of the shroud.

Lippisch, Alexander M.: "THEORETICAL INVESTIGATION OF THE SHROUDED PROPELLER IN FORWARD FLIGHT", Collins Aeronautical Research Laboratory, February 1954

On the basis of momentum theory, the aerodynamic characteristics of a shrouded propeller at different flight attitudes are derived. The conditions of steady horizontal flight as well as the conditions of climbing flight are investigated and the method of establishing certain performance charts are demonstrated.

Lock, C. N. H. & Yeatman, D.: "TABLES FOR USE IN AN IMPROVED METHOD OF AIRSCREW STRIP THEORY CALCULATIONS", Aeronautical Research Committee Reports and Memoranda No. 1674, 22 October 1934.

The theory of this report was modified for use in determining the interference velocities on the blade elements of lightly loaded ducted propellers for which cascade data were not available.

Patterson, G. N.: "DUCTED FANS: DESIGN FOR HIGH EFFICIENCY", Australian Council for Aeronautics, Report ACA-7, July 1944.

A design method for ducted axial flow fans was developed. The momentum and vortex theories as applied to ducted fans were reviewed. The conditions of high fan efficiency show that the choice of the ratio of axial velocity to rotational velocity is of primary importance; while so long as blade sections L/D is large, it is of somewhat secondary importance. The vanes are considered as part of the design problem, but their effect on the overall efficiency was not considered in detail.

Patterson, G. N.: "DUCTED FANS: APPROXIMATE METHOD OF DESIGN FOR SMALL SLIPSTREAM ROTATION." Australian Council for Aeronautics, Report No. ACA-8, August 1944

The report deals with a second method of design of fans with straighteners. (First method in ACA-7). The method allows calculation of the over-all characteristics of a fan designed to operate in a given duct without first carrying out a detail blade design.

Patterson, G. N.: "DUCTED FANS: EFFECT OF THE STRAIGHTENER ON OVER-ALL EFFICIENCY." Australian Council for Aeronautics, Report No. ACA-9, September 1944

The report deals with the design of and evaluation of straighteners for use with axial flow ducted fans.

Patterson, G. N.: "DUCTED FANS: HIGH EFFICIENCY WITH CONTRA-ROTATION." Australian Council for Aeronautics, Report ACA-10, October 1944

The report gives the theory of ducted contra-rotating fans along with two methods of design. It is shown that very high efficiencies are possible with contra-rotation and that these high efficiencies could be attained at larger pressure rises than in the case of a fan straightener combination.

Poole, R.: "THE THEORY AND DESIGN OF PROPELLER-TYPE FANS", The Institute of Civil Engineers, Paper #178, 1935

Sets forth a modified blade element analysis to be applied to propeller fans. Leans heavily on Glauert's vortex theory. Suggests constant-section blading. Not much helpful information pertains to our work. Considers that high solidity blading has same aerodynamic characteristics as isolated airfoils, which is not true as shown by cascade theory.

Reissner, Hans J. & Meyerhoff, Leonard: "A CONTRIBUTION TO THE THEORY AND DESIGN OF UNDERWATER DUCTED PROPELLER SYSTEMS." Polytechnic Institute of Brooklyn, PIBAL Report #178, May 1951

Theory and design of ducted, underwater propulsion systems is presented in detail.

Reissner, Hans J., Meyerhoff, Leonard, and Sohn, David: "ON THE THEORY AND THE DEVELOPMENT OF A DUCT FOR UNDERWATER PROPULSION SYSTEMS." Polytechnic Institute of Brooklyn, PIBAL Report No. 208, April 1953

In the report an example is given of the development of the contour of a duct containing a working propeller in an incompressible fluid. The analysis is based on the axial symmetry of the inflow, and the axial velocity component perpendicular to the propeller plane.

Ribner, Herbert S.: "THE RING AIRFOIL IN NONAXIAL FLOW." Journal of the Aeronautical Sciences, September 1947

The ring airfoil with axis inclined to the stream is investigation by a lifting-line theory. The stream tube that threads the ring is found to deflect like a rigid cylinder. The lift is twice the lift of a flat elliptic wing that spans a diameter and has a quarter the area, and the downwash and ratio of lift to induced drag are the same for both.

Scholes, J. F. M.: "DUCTED FAN: A NOMOGRAM METHOD OF ANALYSIS" Australian Council for Aeronautics, Report ACA-32, February 1947

A graphical method of design for ducted fans based on the work of G. N. Patterson.

Sulzer Brothers Limited: "PROPELLER FAN", Sulzer Technical Review #3, 1941, Winterthur, Switzerland

A semi-technical display of various fans produced by the Sulzer Company. The applications are for cooling and drying and the fans are all used as air sources. This report has no value in the design of ducted propellers.

Thwaites, Bryan: "A NOTE ON THE DESIGN OF DUCTED FANS", The Aeronautical Quarterly Vol III, 1951-52, P 173, Lewis Press, London

This paper deals with a non-iterated solution, in practice, of the blade element equations relating to the design of wind tunnel fans. The work is basic and of value in design of fans operating in a wind tunnel.

Thwaites, Bryan: "A NOTE ON THE PERFORMANCE OF DUCTED FANS", The Aeronautical Quarterly, Vol IV, August 1952, February 1954, P 179, Lewis Press, London

This paper deals with performance of wind tunnel fans; presenting methods of solution of the blade element equations for design and off design conditions.

IB Classical Propeller Blade Element Analysis and Incompressible Flow Analysis - Experiment and Theory

This section contains the abstracts of 21 reports. The subjects covered are: ducts, ducted propellers, bare propellers, wind tunnel fans and isolated airfoil data.

Brown, A. I.: "THE PERFORMANCE OF PROPELLER FANS", Ohio State University Studies, Engineering Series, Engineering Experiment Station Bulletin No. 77, May 1933

This report presents comparison of various commercial ventilating propeller fans. A uniform method of fan rating is presented, in the terms of efficiency, power, and discharge quantity. The work has no direct application to the design of propulsion units.

Daley, Bernard N. and Dick, Richard S.: "EFFECT OF THICKNESS, CAMBER, AND THICKNESS DISTRIBUTION ON AIRFOIL CHARACTERISTICS AT MACH NUMBERS UP TO 1.0", NACA TN3607, March 1956 (formerly RML52G31a)

Normal force, drag, and pitching moment characteristics are presented, together with representative schlieren photographs and pressure distribution diagrams for a group of related NACA airfoil sections varying in maximum thickness, design lift coefficient and thickness distribution.

Hubbard, Harvey H.: "SOUND MEASUREMENTS FOR FIVE SHROUDED PROPELLERS AT STATIC CONDITIONS", NACA TN2024, April 1950, (formerly RML9J28a)

Sound pressure measurement are reported for five shrouded propeller combinations and are compared with those for an unshrouded propeller operating at approximately the same tip speed and power coefficient. In general, results indicate that the best shroud unit from aerodynamic considerations will also produce the minimum sound. An investigation of tip clearance revealed that thrust decreased continuously with increased tip clearance while the sound level did not increase until the clearance became greater than 1% of the diameter.

Küchemann, D. & Weber, J.: "THE FLOW OVER ANNULAR AEROFOILS", Great Britain Ministry of Supply, Translation GDC 10/1133T

The axial flow of propellers with annular fairings is discussed, based on momentum theory,and a theoretical analysis is made to study the mutual interference influences of the ring and propeller. The analysis of tests on a variety of propellers and rings give a qualitative comparison of forces and the relative importance of the ring section parameters in the design of an efficient annular fairing for a propeller.

Küchemann, D. & Weber, J.: "POWER UNIT DUCTS; AND THEORY OF THICK FAIRINGS", Great Britain Ministry of Supply, Reports and Translations No. 990, July 15, 1948

An approximate theory based on the theory of thin cowls is presented for the determination of thick fairings. A comparison of experimental and theoretical values is made.

Küchemann, D. & Weber, J.: "CONCERNING THE FLOW OVER THE COVERINGS OF ANNULAR SHAPES", Translation Report #F-TS-620-RE AMC Wright Field, Dayton, Ohio

Experimental investigation of three annular profiles of finite chord, designed to give increased flow in free flight. Parameters checked were flow, diffuser efficiency and drag. The effectiveness of split flaps was also checked.

Küchemann, D. & Weber, J.: "CONCERNING THE FLOW ABOUT RING SHAPED COWLINGS PART VI - FURTHER MEASUREMENTS ON INLET DEVICES", NACA TM1327, March 30, 1942

Experiments of the flow about ring shaped cowlings, showing the influence of nose radius. A simple rule for the design of ducts with hub is presented.

Küchemann, D. & Weber, J. : "CONCERNING THE FLOW ABOUT RING-SHAPED COWLINGS PART VIII - FURTHER MEASUREMENTS ON ANNULAR PROFILES", NACA TM1328, February 1952

Velocity and drag characteristics are presented from results of measurements on ring-shaped airfoils of rather short length (l/d = .25 - .50).

Küchemann, D. & Weber, J.: "CONCERNING THE FLOW ABOUT RING-SHAPED COWLINGS PART IX - THE INFLUENCE OF OBLIQUE ONCOMING FLOW ON THE INCREMENTAL VELOCITIES AND AIR FORCES AT THE FRONT PART OF CIRCULAR COWLS", NACA TM1329, February 1952

Some tests of a duct with center body at angles of attack.

Krüger, W.: "ON WIND TUNNEL TESTS AND COMPUTATIONS CONCERNING THE PROBLEM OF SHROUDED PROPELLERS", NACA TM1202, February 1949

Results of measurements on a shrouded propeller designed for high advance ratio and high thrust loading are given. Effects of shroud and propeller shapes on the aerodynamic coefficients are presented. The highest measured propulsive efficiency with forward flight speed was 0.71. Comparisons of static thrust are made on the basis of a thrust factor of merit defined as a function of the thrust coefficient and the power coefficient. A theoretical treatment is given and comparison made between theory and test results. This report contains the bulk of the test data presently available.

Lindsey, W. F., Stevenson, D. B., and Daley, B. N.: "AERODYNAMIC CHARACTERISTICS OF 24 NACA 16 SERIES AIRFOILS AT MACH NUMBERS BETWEEN 0.3 AND 0.8", NACA TN1546, September 1948

Section data for propeller blades.

Parlett, Lysle P.: "AERODYNAMIC CHARACTERISTICS OF A SMALL-SCALE SHROUDED PROPELLER AT ANGLES OF ATTACK FROM 0° TO 90°", NACA TN3547, November 1955

An investigation has been made to determine the effects of airspeed and angle of attack on the lift, drag, and pitching moment of a shrouded propeller model. Tests were made of the complete model with the propeller operating and also of the shroud and motor combination with the propeller removed. These tests were made in connection with the design of a vertical-take-off free flight model and the results are presented without analysis as they may be useful in the design and analysis of other aircraft.

Platt, Robert J., Jr.: "STATIC TESTS OF A SHROUDED AND AN UNSHROUDED PROPELLER", NACA RM No. L7H25, February 9, 1948

The results of tests conducted on a dual rotating shrouded propeller and a dual rotating unshrouded propeller are presented. The two propellers differed in design and in the range of blade angles tested. It was found that, for equal power, the shrouded propeller produced about twice as much static thrust as the unshrouded propeller chiefly because the blades of the unshrouded propeller were stalled while the shrouded propeller was unstalled.

Regenscheit, B.: "STATIC THRUST MEASUREMENTS ON SHROUDED PROPELLERS" Great Britain Ministry of Supply GDC 10/5140T

Results of static tests on two shrouded propellers are given. The increase in thrust due to the shroud was found to be as much as 50% of the thrust of the bare propeller. Leading edge rings were tested, and were found to improve the thrust characteristics. An attempt was made to eliminate airstream contraction aft of the duct by the use of a trailing edge ring-slot arrangement, but this method was essentially ineffective.

Regier, Arthur A., Barmby, John G., and Hubbard, Harvey H.: "EFFECT OF CRITICAL MACH NUMBER AND FLUTTER ON MAXIMUM POWER LOADING OF DUCTED FANS", NACA TN1330, June 1947

Flutter tests were made of two wind-tunnel-fan models. The results confirm the stall-flutter theory which predicts much higher flutter speeds at the light lift coefficients for high camber blades. Examples show that the ideal or design lift coefficient of an airfoil is almost the same as the lift coefficient giving the maximum flutter speed.

Reissner, Hans J., Meyerhoff, Leonard: "THEORETICAL AND EXPERIMENTAL RESULTS CONCERNING THE PERFORMANCE OF UNDERWATER DUCTED PROPELLERS, INCLUDING THE RELATION BETWEEN TOTAL THRUST AND THE AXIAL FORCE ON THE DUCT", Polytechnic Institute of Brooklyn, PIBAL Report No. 207, April 1953

The report considers certain theoretical and available experimental data

related to the development of underwater ducted propeller systems of high propulsive efficiency and of a minimum of cavitation. The experimental data were taken entirely from the literature, and the lack of data indicates the need for further tests.

Ruden, P.: "INVESTIGATION OF SINGLE STAGE AXIAL FANS", NACA TM1062, April 1944

The report deals with investigations carried out in the design of a wind tunnel. A fan rotor was developed which had very high efficiency at the design point corresponding to a moderate pressure rise and which , in addition could operate at a proportionately high pressure rise. The first part of the report describes the theoretical investigations; the second, the experiments carried out.

Schwartz, Ira R.: "INVESTIGATIONS OF AN ANNULAR DIFFUSER-FAN COMBINATION HANDLING ROTATING FLOW", NACA RML9B28, April 25, 1949

Two annular diffusers of different conical angles of expansion but constant outer diameters were investigated with rotating flow behind a fan. A wide range of flow distributions was encountered as a result of changes in operating conditions. The 8° diffuser was shown to be substantially better than the 16° diffuser under comparable conditions for the range of Mach Numbers and angles of rotation tested. Sharp reductions in efficiency were found in both diffusers at maximum values of stream rotation. The radial pressure gradient caused by the rotations of the air assisted divergence of the flow; however, at the large angles of rotation, an adverse condition resulted from the inflow of low-energy air which in turn caused separation of the flow on the inner wall.

Scholes, J. F. M., Patterson, G. N.: "WIND TUNNEL TESTS ON DUCTED CONTRA-ROTATING FANS", Australian Council for Aeronautics, Report ACA-14

The report describes and presents results of a series of wind tunnel tests on a pair of ducted contra-rotating fans. The fans used in the test were designed according to theory developed in a recent report of this series (ACA-10). In a check on the theory, it was found to be reliable except where tip loss and the boundary layer in the duct invalidate it.

Stipa, L.: "EXPERIMENTS WITH INTUBED PROPELLERS", NACA TM655, January 1932

Wind tunnel tests were conducted with propellers, isolated, in presences of, and integral with a venturi tube fuselage. The following conclusions were noted:

1. The efficiency of the propeller in presence of the tube was greater than that of the isolated propeller.

2. The efficiency of the propeller integral with the tube was greater than either the isolated propeller or the propeller in presence of the tube.

3. The tube produces a thrust force when the propeller is running.

4. The functioning of the propeller is affected by the inside shape of the tube.

Stivers, Louis S., Jr.: "EFFECTS OF SUBSONIC MACH NUMBERS ON THE FORCES AND PRESSURE DISTRIBUTIONS ON FOUR NACA 64A - SERIES AIRFOIL SECTIONS AT ANGLES OF ATTACK AS HIGH AS 28°", NACA TN3162, March 1954.

Lift, drag, moment, and pressure distribution data are presented for four NACA 64A - series airfoils at Mach numbers from 0.3 to 0.9 and to angles of attack as high as 28°.

IIA Compressor Blade Element Analysis, and Compressible Flow Analysis - Theory

This section contains the abstracts of 10 reports dealing with compressors, cascades, and general fan and propulsion systems.

Eckert, B.: "SUMMARY OF THE RESULTS OF RESEARCH ON AXIAL FLOW COMPRESSORS", Stuttgart Research Institute for Automobiles and Engines

From a lecture summarizing design criteria and techniques for axial flow compressors as of that time. Presently available cascade data and related techniques make this work obsolete for design work.

Eckert, B., Pfluzer, F., and Weinig, F.: "THE INFLUENCE OF DIAMETER RATIO ON THE CHARACTERISTICS DIAGRAM OF THE AXIAL COMPRESSOR", NACA TM1125, April 1948

The influence of diameter ratio is discussed generally and experimental evidence presented. In general the smallest hub size was limited by surge of the blade roots, and the largest hub by the relation of passive to active surface area.

Fickert: "THE INFLUENCE OF RADIAL CLEARANCE OF THE ROTOR ON THE COMPRESSOR EFFICIENCY", BUSHIPS, May 1946, Navy Department, Washington, D.C.

A theoretical influence of tip clearance in terms of volumetric efficiency of the stage is developed. The theory is compared with experiment. The author concludes that a clearance of .05 mm maximum must be held unconditionally. More recent work puts the maximum allowable clearance in terms of percentage of the radius.

Lawrence, W. C. and Hoben, H. E.: "DUCTED FANS EXCEL TURBOJETS AND TURBO-PROPS FOR TRANSPORTS", Paper and Discussion presented at the SAE Southern California Section meeting held November 12, 1953.

In this paper the authors present an economic comparison of three power plant types for future transport aircraft. A discussion of the paper is also contained. The ducted fan mentioned is the by-pass type turbojet.

McCormick, B. W.: "AN APPROXIMATION TO THE LIFT OF A TWO-DIMENSIONAL CASCADE OF AIRFOILS", Journal of the Aeronautical Sciences Vol 22, Number 10, P 730, October 1955

The author presents an approximate solution to the lift of a two-dimensional cascade of airfoils using a vortex at the quarter chord point. The approximation shows very good agreement for high solidities and high inlet angles and for all inlet angles at low solidities.

Perl, W. and Tucker, M.: "A GENERAL REPRESENTATION FOR AXIAL-FLOW FANS AND TURBINES", NACA R 814, 1945

A general representation of fan and turbine arrangements on a single classification chart is presented that is made possible by a particular definition of the stage of an axial-flow fan or turbine. Several unconventional fan and turbine arrangements are indicated and the applications of these arrangements are discussed.

Perl, W. and Epstein, H. T.: "SOME EFFECTS OF COMPRESSIBILITY ON THE FLOW THROUGH FANS AND TURBINES", NACA R 842, 1946

The laws of conservation of mass, momentum, and energy are applied to the compressible flow through a two-dimensional cascade of airfoils. Comparison with corresponding relations for incompressible flow show large differences. The effect of variable axial flow is treated. Some implications of the basic conservation laws in the case of nonideal flow through cascades are discussed.

Reissner, H. J. and Meyerhoff, L.: "ANALYSIS OF AN AXIAL COMPRESSOR STAGE WITH INFINITESIMAL AND FINITE BLADE SPACING", NACA TN2493, October 1951

A method of designing circular blade systems of finite spacing is developed. First, the theory of a flow through a system of infinitesimally spaced surfaces is formulated. Second, the force field in the space between the blades is replaced in the equation of finite spacing by those inertial and pressure terms which are omitted in the equations of infinitesimal spacing.

Weinig, F.: "THE FLOW AROUND TURBINE AND COMPRESSOR BLADES", Reproduced by Code 338 Research and Standards Branch, BuShips, Navy Department, Published in German 1935, Reproduced in English May 1946

A very basic work dealing in a large part with a potential flow through axial-flow machines. More recent cascade data would be more easily used and more accurate in the design of axial flow machines.

Wu, Chung-Hua, Brown, Curtis A. and Prian, Vasily D.: "AN APPROXIMATE METHOD OF DETERMINING THE SUBSONIC FLOW IN AN ARBITRARY STREAM FILIMENT OF REVOLUTION CUT BY ARBITRARY TURBOMACHINE BLADES", NACA TN2702, June 1952

A method is presented to obtain a relatively quick approximate determination of the detailed subsonic flow of a nonviscous fluid past arbitrary turbomachine blades. The solutions are in form of Taylor's series. The solution is an iterative process which shows sufficient convergence in three to four cycles. Because each cycle of computation for compressible flow takes only 16 hours, successive improvement of the solution is practical.

IIB Compressor Blade Element Analysis and Compressible Flow Analysis - Experiment and Theory

This section contains abstracts of 19 reports. The subjects covered are: Compressors, Airfoils in Cascade, and Conditions limiting compressor design.

Ashby, George C., Jr.: "COMPARISON OF LOW-SPEED ROTOR AND CASCADE PERFORMANCE FOR MEDIUM-CAMBER NACA 65-($C_{l_o}A_{10}$)10 COMPRESSOR-BLADE SECTIONS OVER A WIDE RANGE OF ROTOR BLADE-SETTING ANGLES AT SOLIDITIES OF 1.0 AND 0.5", NACA RML54I13, December 27, 1954

A medium camber compressor rotor was tested in a low-speed blower. The tests were made at solidities of 1.0 and 0.5 without guide vanes or stators over a wide range of blade-setting angles and quantity flow rates. The measured over-all and blade-element performance was compared with the performance estimated from cascade data to extend the correlation of cascade and compressor-rotor data over a broad range of blade-setting angles.

Bell, B. E.: "TEST OF A SINGLE-STAGE AXIAL-FLOW FAN", NACA Report No. 729, 1942

Tests were conducted on a fan with a 24 blade rotor, 21 inches in diameter with a solidity of 0.86 and a set of 37 contra-vanes having a solidity of 1.33. The fan was tested for volume, pressure and efficiency over a range of delivery pressures and volumes for a wide range of contra-vane and blade angle settings.

The test results are presented in terms of non-dimensional units in order that similar fans may be accurately designed with a minimum of effort.

Bell, B. E., DeKoster, L. J.: "TEST OF A DUAL-ROTATION AXIAL-FLOW FAN", NACA ARR L 303, December 1942

Tests were conducted on a dual-rotation axial-flow fan with 24 blades in each rotor and with 24 blades in the front rotor and 12 blades in the rear rotor. The outside diameter and the hub diameter were 21 inches and 14-1/2 inches respectively. Pressure and torque coefficients and efficiency were determined and presented as functions of a flow-quantity coefficient.

Bell, B. and DeKoster, L. J.: "THE EFFECT OF SOLIDITY, BLADE SECTION, AND CONTRA-VANE ANGLE ON THE CHARACTERISTICS OF AN AXIAL-FLOW FAN", NACA WR L-304

An axial-flow fan was tested with 6, 9, 12, 18 and 24 blades and with two different blade sections, through a range of contra-vane and blade angles. Changing the contra-vane angle was suitable means of controlling the pressure output of a fan when the quantity range of operation was small.

Bogdonoff, Seymour M. and Herrig, Joseph L.: "PERFORMANCE OF AXIAL-FLOW FAN AND COMPRESSOR BLADES DESIGNED FOR HIGH LOADINGS", NACA TN1201, February 1947

An investigation to determine the effects of loading on the performance of axial-flow fans and compressor blades was carried out in a test blower. The performance of four sets of rotor blades was studied.

Bogdonoff, Seymour M. and Hess, Eugene E.: "AXIAL-FLOW FAN AND COMPRESSOR BLADE DESIGN DATA AT 52.5° STAGGER AND FURTHER VERIFICATION OF CASCADE DATA BY ROTOR TESTS", NACA TN1271, April 1947

An extension of previous work and an improvement of old design charts. The work of this report has been superseded by more recent and extensive cascade data and design methods.

Felix, Richard A.: "SUMMARY OF 65-SERIES COMPRESSOR-BLADE LOW-SPEED CASCADE DATA BY USE OF THE CARPET PLOTTING TECHNIQUE", NACA RML54H18a, November 2, 1954

The 65-series compressor-blade cascade data of RML51G31 is summarized in carpet form, for most convenient use.

Herrig, Joseph L.; Emery, James C., and Erwin, John R.: "SYSTEMATIC TWO-DIMENSIONAL CASCADE TESTS OF NACA 65-SERIES COMPRESSOR BLADES AT LOW SPEEDS", NACA RML51G31, September 14, 1951

The performance of NACA 65-series compressor blade sections in cascade has been investigated systematically in a low-speed cascade tunnel. The results of the investigation indicate a continuous variation of blade-section performance as the major cascade parameters, blade camber, inlet angle, and solidity were varied over the test range. Summary curves have been prepared to enable compressor designers to select the proper blade camber and angle of attack when the compressor velocity diagram and desired solidity have been determined. This data is available in carpet form in NACA RML54H18a.

Herrig, Joseph L.; Emery, James C. and Erwin, John R.: "EFFECT OF SECTION THICKNESS AND TRAILING EDGE RADIUS ON THE PERFORMANCE OF NACA 65-SERIES COMPRESSOR BLADE IN CASCADE AT LOW SPEEDS", NACA RML51J16, December 13, 1951

Tests of an airfoil with varying thickness in cascade to determine the effects of thickness. Tests of a 10% thick section with modified trailing edge radius to determine the penalties incurred with more practical trailing edges was also made. It was found that a generous trailing edge radius could be used without penalty.

Kahane, A.: "CHARTS OF PRESSURE RISE OBTAINABLE WITH AIRFOIL-TYPE AXIAL-FLOW COOLING FANS", NACA TN1199, March 1947

Charts are presented to show the pressure rise that is obtainable in an engine-cooling installation with a typical airfoil-type propeller-speed fan. The charts cover fans of the stator-rotor, rotor-stator, and rotor alone configurations, with blades incorporating both the highly cambered 65-series blower-blade sections and the conventional low-cambered airfoil sections. Use of the charts is illustrated in a sample calculation.

Kuhane, A.: "INVESTIGATION OF AXIAL-FLOW FAN AND COMPRESSOR ROTORS DESIGNED FOR THREE-DIMENSIONAL FLOW", NACA TN1652, July 1948

An investigation has been conducted to determine whether three-dimensional flows may be efficiently utilized in axial-flow fan and compressor rotors so that spanwise load distribution may be suitably varied to obtain high pressure rise. The results indicate that the three-dimensional flows may be utilized with high efficiency and that the three dimensional theory used in conjunction with two-dimensional cascade data is sufficiently accurate for design purposes.

Lieblein, Seymour: "TURNING ANGLE DESIGN RULES FOR CONSTANT-THICKNESS CIRCULAR-ARC INLET GUIDE VANES IN AXIAL ANNULAR FLOW," NACA TN2179, September 1950

A survey of data from investigations of axial-flow-compressor inlet guide vanes with circular-arc, constant-thickness sections and axial air inlet was conducted to establish a relation between vane camber and air turning angle for use in the design of this type of vane.

Lieblein, Seymour; Schwenk, Francis C., and Broderick, Robert L.: "DIFFUSION FACTOR FOR ESTIMATING LOSSES AND LIMITING BLADE LOADINGS IN AXIAL-FLOW-COMPRESSOR BLADE ELEMENTS", NACA RME53D01, June 8, 1953

A limiting-blade-loading parameter for axial-flow-compressor blade elements was derived from the application of a separation criterion used in two-dimensional boundary-layer theory to a typical suction-surface velocity distribution of a compressor blade element at design angle of attack.

Mankuta, Harry, and Guentert, Donald C.: "INVESTIGATION OF PERFORMANCE OF SINGLE-STAGE AXIAL FLOW COMPRESSOR USING NACA 5509-34 BLADE SECTIONS", NACA RME8F30, September 30, 1948

An investigation was conducted to study the performance of a single-stage axial-flow compressor using blades with an NACA 5509-34 airfoil section. The performance of the rotor and stator blade rows is presented separately on the basis of three different measures of blade loading turning angle, lift coefficient, and a loading factor defined as the ratio of the change in tangential velocity through the blades to the mean axial velocity.

Mankuta, Harry, and Guentert, Donald C.: "SOME EFFECTS OF SOLIDITY ON TURNING THROUGH CONSTANT-THICKNESS CIRCULAR-ARC GUIDE VANES IN AXIAL ANNULAR FLOW", NACA RME51E07, August 24, 1951

An investigation was conducted on sheet metal, circular-arc, compressor inlet guide vanes in an annular cascade to determine the effect of solidity on turning through a blade row. An equation similar in form to Constants' rule, which may be used to predict turning angles in cascades of configuration similar to that of this investigation, was obtained from the data. This equation may be used to extend the applicability of existing guide-vane data and design rules to other solidities.

Savage, Melvyn: "ANALYSIS OF AERODYNAMIC BLADE-LOADING-LIMIT PARAMETERS FOR NACA 65-(C_{l_o} A_{10})10 COMPRESSOR-BLADE SECTIONS AT LOW SPEEDS" NACA RML54L02a, April 24, 1955

A cascade loading - limit parameter for incompressible axial-flow compressor-blade elements is presented. The loading-limit parameter was evaluated from blade-surface-measured pressure distributions. The ratio of the suction surface maximum static pressure used to the difference between the stagnation and static pressures at the point of maximum surface velocity is the parameter and is referred to as the C-factor.

Struve, E.: "THEORETICAL DETERMINATION OF AXIAL FAN PERFORMANCE", NACA TM1042, April 1943

This is a complete treatment of axial fan design in five sections. 1. Exposition of the blade element theory. 2. Discussion of the physical basis of the phenomena in fan operation and generalization to different operating conditions. 3. Explanation of the new modifications of axial fan computation, whereby use is made of the pressure and power coefficients. 4. Method of determining axial fan performance. 5. Comparison of theoretical and experimental results.

The design methods of this report have been superseded by recent exhaustive cascade data available from the NACA. The material, however, is basic and therefore of interest as background material.

Weske, J. R.: "AN INVESTIGATION OF THE AERODYNAMIC CHARACTERISTICS OF A ROTATING AXIAL-FLOW BLADE GRID", NACA TN1128, Feb. 1947

Tests were performed on a 36-inch diameter axial flow, 12-bladed grid that incorporated a rotating shroud ring. Pressure distributions and aerodynamic characteristics of blade sections are presented.

Wright, Linwood C. and Schwind, Richard.: "THROAT-AREA DETERMINATION FOR A CASCADE OF DOUBLE-CIRCULAR-ARC BLADES", NACA RME55H25a, November 15, 1955

A procedure is derived for approximating the throat area and the choking incidence angle for a compressor geometry wherein the throat area is at the inlet to the cascade of double-circular-arc blades and the leading-edge radius is 0.15 of the maximum thickness. Charts for determining the throat area are presented.

An empirical relation between the choking incidence angle or an inlet relative Mach number of 1.0 and the minimum-loss incidence angle is presented using the available test results for rotor tip, pitch and hub sections.

Th[illegible] report applies mainly to rotor speeds whereas the relative inl[illegible] [illegible]ch number is transonic. Limitations upon the accuracy of the procedure are given.

Conference Trip Reports

Conferences were held with various agencies that were interested in ducted propellers. Visits were made to the NACA installations at Langley Field, Virginia and at Cleveland, Ohio; to the propeller laboratory at WADC; to the University of Wichita; to the David Taylor Model Basin; to Kaman Aircraft; to Collins Radio Corporation; to Princeton University; and to the ASTIA Document Service Center. The reports of these conferences are contained in this section. The information gathered during these conferences substantially increases the available information pertinent to the design of ducted propellers.

Conferences on Ducted Propellers for VTOL Transport
at the NACA Langley Field

On June 9 and 10, 1955 Messrs. O'Malley, Zabinsky and Sing, of Bell Aircraft, visited the NACA at Langley AFB, Virginia, to discuss the general subject of ducted propeller design for application to the VTOL Assault Transport Study Contract (N-onr-1675-(00)). The following NACA personnel were contacted in a series of 3 conferences:

Mr. Axel Mattson - Head 8' Transonic Tunnel
Mr. Robert J. Platt - 8' Transonic Tunnel
Mr. Marion McKinney - Asst. Head Free Flight Tunnel Section
Mr. Charles Zimmerman - Asst. Chief, Stability Research Div.
Mr. Richard Lindsay - Head, 24" High Speed Tunnel
Mr. Willard Westphal - Cascade Aerodynamics
Mr. John R. Erwin - Head, Cascade Aerodynamics

In each case the purpose of our study was outlined and our objective stated as the design of a fan which could develop 22,500 pounds of thrust.

Conference with Mr. Mattson and Mr. Platt

Mr. Mattson arranged the discussion with Mr. Platt but did not take part in the conference. Mr. Platt is presently assigned to the 8' transonic tunnel. He is the only man at this installation who has conducted formal experimental studies on ducted propellers. A series of tests were reported in February 1948 as RML7H25 "Static Tests of a Shrouded and an Unshrouded Propeller," by Robert J. Platt, Jr. Mr. Platt had not done any of this work recently so it was necessary for him to limit his discussion to the tests of this report.

The shrouded propellers described in this report had not been tested in forward flight conditions. They had been designed for a 250 mph application considering that the augmented static thrust was of secondary importance. The analysis had been based on simple momentum theory in conjunction with blade element theory. The exit pressure was assumed to be ambient and the resulting calculated thrust was verified quite closely in experimental testing. Tests were performed on a 48" diameter propeller with shroud lengths of less than 1 diameter. Two contra-rotating propellers had been used, the front one carrying five blades and the rear one seven blades. Mr. Platt estimated that the props had a total pressure ratio of about 1.05. One of the principle difficulties he had encountered was due to side winds on the shroud. Even moderate winds (5 mph) appeared to separate the downstream lip of the shroud resulting in a large increase in the noise level. Unfortunately thrust measurements were not made during this phase of the tests.

Mr. Platt agreed that the effects of separation might be eliminated if high fan pressure ratios were used to cause higher inflow velocities but he had not verified this experimentally. The use of exit area larger than fan disk area was one of the items investigated in this series of tests and it appeared that the thrust of the unit could be raised by increasing the flow of air through the fan at the same power setting. Complete details on this work are noted in RML7H25.

Mr. Platt questioned the necessity for using a shroud on the propeller. He pointed out that a larger diameter unshrouded propeller might be a lighter installation. It was noted that our design was based on keeping the diameter as small as possible by using the shroud as an aerodynamic augmentation to the static thrust of the propeller. The use of the shroud to cover the rotating blades and the elimination of the 90° side wind on the propeller in hovering were also features of value in such a comparison. It was agreed that, in our case, the diameter of the shrouds would be a critical design element.

Mr. Platt was unable to discuss any more recent tests on static thrust of shrouded propellers but he did note the existence of tests on the noise levels of such installations. He discussed TN2024 "Sound Measurements for 5 Shrouded Propellers at Static Conditions" by Harvey Hubbard. These tests had examined four different shapes and 3 different length shrouds. He was particularly interested in the fact that this report showed a rapid drop off in effective thrust as the tip clearance of the blade increased in percentage of blade diameter.

Another report, published by the Polytechnic Institute of Brooklyn, was mentioned. This report was entitled "A Contribution to the Theory and Design of Underwater Ducted Propeller Systems" by Hans J. Reissner and Leonard Meyerhoff. (PIBAL Report No. 178). Although this report applied to hydraulic propellers, it is possible that the theoretical approach will be of interest.

Mr. Platt noted that the shrouded propeller model he had tested had been designed on the basis of the cruise condition. The side wind separation phenomena was a function of shroud nose radius. They had measured forward flow and high peak pressure on the shroud lip. He also noted that the lip separation during testing had been easiest to avoid on the medium length shroud. He mentioned shroud lengths of 28.8, 19.2 and 9.6 inches, in conjunction with the 48 inch diameter propeller. These lengths differ from the data reported in RML7H25. He had used the 16-series blade elements in his design.

Mr. Platt examined the partial bibliography we have prepared to date. He noted that the cascade work completed by Bogdonoff was considered obsolete and suggested we talk to Mr. Erwin in Cascade Aerodynamics. He also suggested a conference with Mr. McKinney who had done the free flight work on the shrouded propeller platform and with Mr. Lindsey who had done the two-dimensional tests on the original 16-series propeller sections.

<u>Conference with Mr. Zimmerman and Mr. McKinney</u>

This conference was held at the free flight tunnel section. Mr. Zimmerman was quite familiar with the Navy Contract we are working on. Mr. McKinney described the design of the shrouded propeller models which were used in the tests of the man carrying platforms similar to the Hiller Platform. He pointed out that they had not been trying to design a shrouded propeller but had merely used this shroud as structural support for the platform and to protect the pilot from rotating blades. He believed that a lighter installation could be made without using the shroud and that the same thrust-horsepower relationship could be established by using a larger diameter propeller.

His design procedure had been quite simple. He used straight walled shrouds and assumed that the exit static pressure would be equal to ambient conditions. Then using an incompressible momentum analysis he established the velocity at the propeller and applied a blade element analysis to define the blade shapes necessary to establish his assumed fan pressure ratio. His shrouds ranged in length from a half to a full diameter. He had used an 18-inch diameter propeller. His experimental thrust values checked with his theoretical thrust calculation. Half the thrust of the unit came from the propeller and half the thrust came from the shroud.

They had not made any systematic studies of the fan and shroud but had merely tried to get a thrust level high enough to support their model. He had collected the information which was available on this design, however, and was putting it together in a data report. This report was entitled "Aerodynamic Characteristics of a Small Scale Shrouded Propeller at Angles of Attack from 0 to 90 Degrees" by Lysle P. Parlett. The report will be available in about 3 months. The results showed some influence of nose radius on the efficiency of the propeller. They had used a beaded ring of fixed radius at the nose. They found that the outer contour could be cut off without an appreciable loss in efficiency. On the 18" propeller a linear variation of efficiency existed as the nose radius increased. It ranged from .71 at a nose radius of 0.4 inches to .90 at 3.2 inches. He had calculated an efficiency by momentum theory of .64 at zero nose radius. In making their tests they had not noticed the sensitivity to side winds noted by Platt.

They used a 1/8" tip clearance on their 2-bladed, 18-inch diameter propeller. They had a tip chord of only 3 inches. They had not noticed any appreciable decrease in thrust due to this gap which made Mr. McKinney speculate that the gap was a function of diameter rather than tip chord.

Mr. McKinney showed us another collection of data which will not be published. This contained a series of pressure distributions measured under conditions of a side wind. These results showed that the side wind increased the pressure distributions on the upstream lip and decreased it on the downstream lip of the shroud, thus applying a moment which tended to turn the shroud out of the wind. The force was developed by changing both the normal force and side force on the shroud lip. He mentioned that this condition acted as a limiting speed effect on the Hiller platform. An additional case had been tested by using a sharp lip extension of the duct wall. Since this had no area to support a normal force, the side wind effect merely changed the side force components in the pressure distribution. The same general effect was noted, i.e. build up of pressure distribution on the inner surface of the upstream lip and deterioration on the inner surface of the downstream lip.

Mr. McKinney concluded the discussion by showing a movie of model tests recently completed on the rotating wing and propeller version of a transport type VTOL. (This would be similar to the concept now being studied by Hiller). The movie showed a VTO, hovering with the fuselage horizontal and the wing rotated 90° to level flight, and finally rotation of the wing structure to let the airplane transition into level flight. There was no difficulty noted in this transition. The airplane was a 1/12 scale dynamically similar model of a 115,000 pound airplane which utilized 4 engines and propellers. The wing span was almost completely submerged in the slipstream of these four propellers. This concluded the discussion with Mr. McKinney and Mr. Zimmerman.

Conference with Mr. R. Lindsey

The purpose of this conference was to get the latest information on two dimensional airfoil tests which could yield satisfactory blade element parameters. The conference was held in the office of the 24" high speed tunnel section. Mr. Lindsey brought us up to date on available published material and commented on blade section characteristics. He felt that thickness was, by far, the greatest influence on unsteady forces. He had completed tests down to 2% thickness. Pushing for the highest critical Mach numbers on the blade tips would lead him to recommend a .2 cambered section rather than the .5 camber we had proposed. He noted that the 65A series airfoils were probably superior to the 16 series from a panel load consideration. He showed a short movie to demonstrate the effect of thickness on oscillating shocks and corresponding loads on the sections. The use of the 3% thick sections, as might be expected, greatly reduced the intensity of such shock patterns.

He noted that the information on section profiles available in TN1546 which we have been using, has been superseded in some cases by using open circuit tunnels rather than closed circuit tunnels. He noted that comparisons of these data with later reports would not be reasonable. He listed 6 reports for our consideration.

Mr. Lindsey commented on the favorable effects of camber on very thin sections (2%) and also on the Reynolds number effects they had encountered in section tests. They use a one or two inch chord and about an 18-inch span. He said they required a $Rn = 1.7 \times 10^6$ for 12% airfoils and suspected that about the same value should be used on 6% thick sections. He showed some data on several airfoils where only the chord length had been changed and this had caused separation. He made a few observations on the radial flow boundary which could exist on propellers and the tendency of an "old" boundary layer to induce separation whereas a "young" boundary layer could sustain a relatively sharp adverse pressure gradient.

We discussed the possibilities of substituting cascade data for two-dimensional airfoil data. It was evident that this was a function of our choice of pressure ratio and the subsequent number of blades required. Mr. Lindsey noted that the cascade aerodynamics people at Langley had done most of their work with a constant section thickness of 10% and had concentrated on varying other parameters in their study. Mr. Lindsey escorted us to the West Area of the field for discussions with this group.

Conference with Mr. Erwin and Mr. Westphal

The Cascade Aerodynamics Group does most of the work required by Lewis Laboratories. They concentrate on fan and compressor designs and in making cascade tests to determine design parameters.

They were interested by our approach and were also concerned about why we were using the shroud design. Their experience had been related to fan designs in that they were testing transonic compressors in a closed circuit from atmosphere. Their general design procedure was to assume the static pressure at the duct exit would be ambient and to use a momentum analysis to define the flow at the fan. Then using cascade data, which had been determined at low Mach numbers, they made a detail design of the fan itself. They had found this low speed cascade data satisfactory in the design of fans with total pressure ratios up to 1.35, axial flow velocities of 650 feet/second and tip speeds of 1000 feet/second.

They had also designed a transonic compressor with a total pressure ratio of 1.25 with a mass flow of 47 pounds of air per square foot of frontal area. Critical flow is 49 pounds per square foot. In this case the low speed cascade data had also given satisfactory results. They felt that these data would be sufficient to design fans from about 1.1 pressure ratio and above provided that the solidity range was not too low. They usually design to a tip clearance of about 1% of the radius.

Mr. Erwin suggested four basic references.

Conference on Ducted Propellers for
VTOL Assault Transport at WADC

On June 16, 1955 Messrs. O'Malley, Macey and Sing of Bell Aircraft visited WADC, WPAFB, Dayton, Ohio to discuss the general subject of ducted propeller design for application to the VTOL Assault Transport Study Contract (N-onr 1675-(00)). The following personnel were contacted:

Mr. W. T. Grady	- Chief Aerodynamicist, Prop Lab.
Mr. Dana Webb	- Aerodynamicist, Prop Lab.
Mr. W. Grieg	- Cargo and Training Division, Weapon Systems
Mr. F. Orazio	- Design Branch, Aircraft Lab.
Mr. R. Bowman	- Design Branch, Aircraft Lab.
Capt. Anderson	- (Proj. Engr. ATV) Flt. Controls Lab.

Conference at Propeller Laboratory (Mr. Grady and Mr. Webb)

Mr. Webb said that the Propeller Laboratory had not done too much work on shrouded propellers up to a year ago. At that time they became interested primarily as an aid in determining how to evaluate such proposals. They feel that the shrouded propeller has advantages since it reduces tip losses and propeller diameters.

Mr. Webb said that their studies had led them to conclude that the shroud gave an exit static pressure which was ambient. He noted that their previous approach had been based on the assumption that ambient pressure occurred far downstream. He had become convinced as a result of studying Patterson's work in the Australian Council for Aeronautics Report No. 14. He argued that the experimental pressure data in this report indicated essentially ambient condition at the exit. This had to be based on an interpolation between a group of points at one station and a single point at another. He was quite confident that this was a valid conclusion and felt that it changed their outlook on axial flow velocities completely. He mentioned Platt's work at NACA and Kuchemann and Weber's data as indicating the same general trend.

Mr. Grieg asked some interesting questions. He was concerned by the fall off in thrust of the ducted propeller as speed increases. The thrust-horsepower relationships presented in our first studies were discussed. He mentioned the thrust to engine weight relationship to determine whether such an approach would be competitive. A number of 4 pounds of thrust per pound of engine was discussed. It was agreed that this was a competitive figure. Mr. Grieg was quite concerned by the use of enough power to take off vertically in conjunction with cruising speeds of 300 mph. He was particularly concerned about the economic feasibility of large power, high fuel consumption and low cruise speed. In his opinion this was far too much power for this speed range. He noted that speed did not seem to be a problem and estimated that low transonic speeds might be possible. He agreed that this would be more compatible with the power relationship.

The gyroscopic effects of the propeller were mentioned by Mr. Grieg. It was noted that we did not expect them to adversely influence the stability and control of the airplane since the angular momentum would generally be less powerful than that encountered in high speed jet engines.

Variable blading was discussed and it was agreed that stator variation gave essentially the same results. It was noted that some of the experiments they had attempted resulted in such high stator angles that prohibitive drag resulted.

The shroud length and landing gear relationship was discussed. The advantages of the rolling take off were apparent to all concerned. The use of such a rolling gear in conjunction with the rotating shrouds put a limit on the shroud length. The propeller laboratory people were not sure of the influence of this parameter on the propeller although it appeared that a relatively short shroud should provide a substantial increase in thrust.

Webb mentioned that Curtiss propeller Division had done some work on ducted propellers and said that Hank Borst of that company would be familiar with the results. He did not know of any recent work by Hamilton Standard but suggested we talk to Carl Rohrbach at that company. Although many of these people did not have detailed ducted propeller studies, he was sure that they would have interesting ideas on the subject.

Although WADC has not done any testing they would anticipate that their first work would involve experiments to determine the relationship between shroud length and diameter, the influence of variable stators, the isolation of the shroud forces, the pressure distribution in the shroud, the velocity through the shroud, the effects of pitch and yaw on external forces and the stresses on the propeller blades. They would put a model on one of their rigs for testing.

The remainder of the discussion at the Propeller Laboratory was devoted to brief comments on several miscellaneous items:

a. The 16 series airfoil section gives them some structural advantages due to the larger trailing edge radius.
b. They have not experienced much difficulty with thin blades. The higher section speeds give them a better flutter boundary.
c. They have used 65-series sections on some inboard sections.
d. They have run up to tip speeds of M = 1.5 and forward speeds of M = .9.
e. They have experimented with hollow steel blades.
f. They have substantial test time on a blade varying from 5-6% at root to 2% at the tip on the F84H program. Some test work has also been done on 4% root and 1-1/2% at the tip.
g. They plan to decrease thickness primarily to save weight. Performance is not much of a problem.

h. Blade camber has usually been set at zero on the basis of work accomplished by United Aircraft some time ago which showed this to be optimum. Recent high Mach number tests indicate that perhaps .3 camber is better at high lift coefficients and high Mach number.
i. They have gone as high as .7 camber at the blade root on some piston engine installations.
j. They have generally limited their test experience to 4 blades or less. They have a few dual rotation 8 bladed tests and a few 6 or 8 bladed single rotation tests.
k. They think the NACA ran a few 8 to 10 bladed experiments some time in the past. (Perhaps Platt's dual rotation, 5 and 7 blades?)
l. Transonic blade section data has only recently been acquired. They have not collected much experience on the newer sections.

<u>Conference at Aircraft Laboratory</u> (Mr. Orazio, Mr. Bowman and Capt. Anderson)

Mr. Orazio's group had not done any original work on ducted propeller airplanes. They had evaluated one liaison type airplane based on the G.E. X-84 type engine.

They said that two or three contractors had been in with ideas similar to ours (ducted) and also with the rotating wing and vaned wing approach. Mr. Orazio thought there was a definite need for a short haul transport such as we suggested. He felt that the shrouded propeller was a good ideal although he had no factual data to back this up.

Orazio stressed the importance of turn around capability for a short haul transport. He thought our idea of overload and rolling take off gave our scheme much flexibility. He mentioned a Stanford study on the transport situation which he thought was being performed for Mr. Wurzbach's group. He feels there is a lot of work to be done with this new concept of short haul since the large transports are almost completely sized by their range capability.

He was interested in the fact that Mr. Grady at Propeller Laboratory was studying ducted propellers. He did not feel that such a study could be completed without parallel studies on configurations.

Conference on Ducted Fans
at the University of Wichita

On June 28, 1955 Messrs. J. O'Malley, E. Sing and J. Zabinsky visited the Municipal University of Wichita to confer on ducted propeller problems. The conferees from the University were Dean K. Razak, Professor R. Wallace, and Professor H. B. Helmbold.

At the time of our visit they had not done any experimental work on ducted propellers. Professor Helmbold had started a theoretical study. His study followed the approach of Kucheman and Weber. He felt that the large advantage of a ducted propeller would be in improving the static thrust. Although many writers on the subject have discussed the possibility of maintaining a constant internal advance ratio or fixed pitch, on a ducted propeller, Professor Helmbold did not believe that this had been proved. He showed us his basic relationship comparing the velocity at the propeller for bare and ducted propellers.

For the bare propeller the classical expression is:

$$V_p = V_o + wa/2$$

where V_p is the velocity at the propeller

V_o is the free stream velocity

wa is the velocity increment added to the stream far behind the propeller

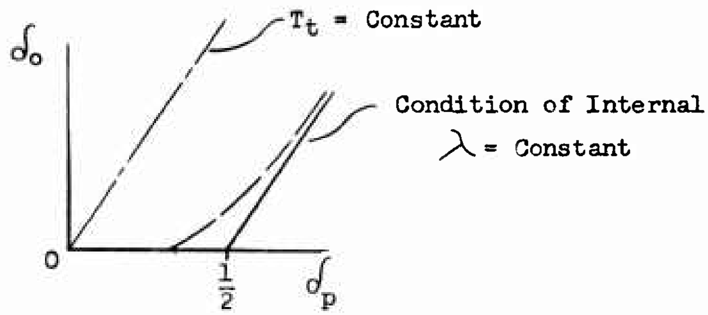
For the ducted propeller his equation became:

$$V_p = (1 + \delta_o)V_o + (1/2 + \delta_p)wa$$

where δ_o is an additional velocity at the propeller, in fractions of the free stream velocity V_o, due to the duct shape and is a function only of the duct shape and internal area variation. δ_p is another velocity increment in terms of the downstream velocity increment, w_a, due to the action of the propeller in the duct.

Professor Helmbold had not considered the effects of pressure ratio or propeller disc loading. He was interested in our ideas and planned to include the effects of highly loaded propellers in his study.

He derived a relationship between δ_o and δ_p



The solid line at the right is for an infinite duct and can only be approached by a finite duct as shown by the dashed line. The dot dash line shows the relationship between δ_o and δ_p for a constant thrust system.

They were in the process of experimentally examining the effects of BLC on a biplane arrangement with different air flows over the wings. The first type was undisturbed free stream flow over the wings with a blowing flap on the upper wing and a sucking flap on the lower. The same wing configuration would be investigated with flow from bare propellers and ducted propellers to examine static lift possibilities.

In the discussion of the static thrust of ducted propellers, Prof. Helmbold pointed out that the basic effect of the duct was the suppresion of the tip vortex by the end plating on the blades. He also mentioned that the theoretical Bendeman factor of merit of 1.26 or $\alpha = 1$ had been exceeded in experiment by Dr. Lippisch. The Bendeman factor for ducted propellers is:

$$K \approx (2 \alpha)^{1/3}$$

where α is the ratio of free stream tube area far behind the propeller to flow area at the propeller.

Professors Wallace and Helmbold outlined the test program they were planning. In order to realize the full potential of the ducted fan under static conditions they were going to investigate methods of improving the diffusion characteristics of the duct. They were thinking of BLC application to the exit of the diffuser and planned to simulate this with slotted flaps. In addition to the duct exits, they were interested in investigating the effects of slots in the leading edge to control entry separation. During the discussion of entry geometry they pointed out that a leading edge radius tangent to a straight section would cause undue boundary layer growth and early separation even though the nose radius was generous.

Analytically they explained this as being a result of a discontinuous second derivative at the point of tangency which caused flow accelerations leading to rapid boundary layer growth with early separation.

The partial bibliography was shown to Professor Helmbold. He was familiar with many of the German reports, as well as the authors. He was able to advise us as to the desirability of having these reports translated. He reviewed the reports which he had compiled for ONR and commented on the German texts. In most instances he felt the material had been superseded or compiled in more accessible form. The work of Kuchemann and Weber, and Kruger were he felt the best available.

In the discussion of diffusers they commented on the cusp type, short length diffuser developed at Princeton. In general, they felt that the mechanics of this process was not well understood and that it would be difficult to design a system and be sure that the diffusion would work. The Princeton development was considered lucky and the direct result of having an unlimited power source available. The cusp diffuser was considered very expensive power wise.

Conference on Ducted Propellers for VTOL Transport at the NACA Lewis Laboratory

On July 7 and 8, 1955, Messrs. Jackes and Macey of Bell Aircraft visited the NACA Lewis Flight Propulsion Laboratory at Cleveland, Ohio, to discuss the general subject of ducted fan design and its application to the VTOL Assault Transport Study Contract (N-onr-1675-(00)). On July 8, Mr. O'Malley joined the group for that day's discussions. During the two-day visit, the following NACA personnel were contacted:

Mr. Clinton Wilcox	- Propulsion Systems Analysis Branch
Mr. Michael Behun	- Propulsion Systems Analysis Branch
Mr. Seymour Lieblein	- Compressor & Turbine Division
Mr. Arthur Medeiros	- Compressor & Turbine Division
Mr. Harold Finger	- Compressor & Turbine Division
Mr. Wilson Hunter	- Engine Research Division Staff
Mr. John Sanders	- Engine Controls Branch
Dr. John Evvard	- Chief, Supersonic Propulsion Division
Mr. Edgar Cortright	- Chief, 8 x 6 Tunnel, Supersonic Propulsion Division

In each case, the over-all concept and purpose of our study was outlined.

July 7

Conference with Mr. Wilcox and Mr. Behun

Mr. Wilcox and Mr. Behun are connected with the Propulsion Systems Analysis Branch, and most of their work has been concerned with propulsion systems analysis, cycle analysis, etc. They have done no work on what they would consider a ducted propeller, although both have some experience in cycle analysis of ducted fan engines.

Most of the conference with Mr. Wilcox and Mr. Behun concerned the adaptation of turboprop powerplants to our particular needs, expecially with regard to water injection. Mr. Wilcox stated that he does not know of any present day turboprop engine on which water injection has been used. The main limitation on the use of water injection is the strength of the engine gearing. It was noted that most commercial turboprops are limited as far as gearing stresses are concerned. Mr. Wilcox stated that water injection will tend to increase the pressure ratio slightly. Both men agreed that 100% augmentation is feasible with water injection, provided that the manufacturer designed the engine to take the additional gearing stresses; or to make up for power lost due to ambient conditions.

Mr. Wilcox and Mr. Behun agreed that the fan pressure ratio would be essentially constant with forward speed over the speed range considered. It was noted that most turboprop engines are designed for use with variable pitch propellers, and operate at essentially constant speed. It was felt that since varying the turbofan thrust without varying pitch necessitates unusually large speed changes, some engine operating problems might be encountered.

Mr. Behun stated that he believed that the pressure at the exit of the ducted fan would be ambient for fairly high pressure ratios. Mr. Wilcox said he thought this could be justified in Glauert's "Aerofoil and Airscrew Theory".

Mr. Wilcox stated that he was of the opinion that a .3 hub-diameter ratio was satisfactory for long blades. He pointed out that for compressors, the tip might be critical as far as choking is concerned and the hub diameter is usually determined by the blade setting, number of blades, etc.

Mr. Wilcox then suggested that we talk to the people in the Compressor and Turbine Division.

<u>Conference with Mr. Lieblein, Mr. Medeiros and Mr. Finger</u>

Mr. Lieblein, Mr. Medeiros and Mr. Finger are connected with the Compressor and Turbine Division, and have done much work on the design of axial flow compressors. They were quite interested in the design problem of the ducted fan.

Mr. Lieblein gave the opinion that, for high pressure ratios, the pressure on the duct exit may not be truly ambient. Trailing edge conditions and the velocity profile at the exit would be significant parameters. Mr. Finger stated, however, that for jet nozzles the exit pressure is essentially ambient for jet velocities below sonic. All present concurred in the belief that, in our case, the assumption of ambient pressure is sufficient. It was pointed out that the axial approach velocity may not be uniform for ducts of large curvature. Mr. Lieblein also stated that the axial velocity changes in passing through the fan due to compressibility; and also varies across the annulus, but if the variation is less than 10% they usually neglect it in their design work.

Mr. Lieblein stated that a 10% blade was too thick for a tip speed of M = .8. The maximum tip speed for a 10% section would be limited by choking and solidity. It was pointed out that lift coefficient and turning angle would not be markedly affected by changing thickness but the drag varies. Very insignificant changes in turning angle are obtained with increasing Mach number up to the point of high shock losses although drag increases. This group is used to working with high relative tip speeds, well into the transonic range. It was also pointed out that changing the thickness distribution does not affect the turning angle appreciably as long as the camber remains the same. For this high Mach number type of compressor, NACA has been using circular arc blades with good results. Mr. Lieblein presented the following table of thickness ratios which is used more or less as a rule of thumb in their design work:

Rel. Mach No.	.4	.5	.6	.7	.8	.9	1.0
t/c	.10	.09	.08	.07	.06	.05	.04

This thickness schedule was recommended provided the minimum passage area is not choked at any point. Mr. Lieblein also stated that he would not recommend a thickness ratio of less than 4% at the tip. He noted that the blade loading limit parameter must be examined to minimize losses for any given design - simply setting the blade at the design angle is not a guarantee of low losses.

This group generally uses a free vortex distribution and radial equilibrium in its design work. The following reports were recommended as examples of common design procedure:

"Experimental Investigation of a Five-Stage Axial-Flow Research Compressor with Transonic Rotors in All Stages. I - Compressor Design", by D. M. Sandercock, K. Kovach and S. Lieblein. NACA RME54F24, September 8, 1954.

"Investigation of a High Pressure-Ratio Eight-Stage Axial-Flow Research Compressor with Two Transonic Inlet Stages. I - Aerodynamic Design", by C. H. Voit NACA RME53I24, December 4, 1953.

It was pointed out that for large pressure ratios, on the order of 1.2, it might be necessary to use inlet guide vanes with a tip Mach number of only .80. It was agreed, however, that it is more desirable to raise the tip speed, than to use inlet guide vanes. All members of this group agreed that an efficiency of 90% could probably be easily realized for the type of unit described, with large dimensions (10 foot diameter), and low tip Mach numbers. Mr. Lieblein stated that Patterson's relations for achieving good efficiency are good for rough screening of a design, but are not strictly true for compressible flow.

This group generally agreed that thrust modulation would be a very difficult problem. Mr. Finger stated that it is difficult to calculate off-design conditions. There is no good method for off-design calculations; the best procedure being to find a similar compressor section if possible. Trial and error methods may be used, by assuming an axial velocity and matching the continuity equations, energy equations, etc. It was noted that with a free vortex design, a higher hub-tip ratio than .30 would be less sensitive to off-design operation. Mr. Finger thought that speed reduction alone would not be good enough for thrust reduction over the range desired. He suggested blocking the inlet area to reduce thrust. In his opinion, the combination of cutting speed and blocking the area directly in front of the fan may not cut the efficiency too much. In connection with off-design operation, it was stated that a hub-tip ratio of .3 may be too low. It was agreed that a free-wheeling power turbine would make our matching problem much simpler.

July 8, 1954

On July 8 the Bell Aircraft group contacted Mr. Wilson Hunter of the Engine Research Division Staff. Mr. Hunter was very interested in our problem, and made arrangements for us to contact Mr. Sanders, of the Engine Controls Branch, and Dr. Evvard and Mr. Cortright of the Supersonic Propulsion Branch. Mr. Hunter sat in on both of these conferences.

Conference with Mr. Sanders

Mr. Sanders is connected with the Engine Controls Branch. The main purpose of this conference was to discuss ways and means to obtain a large range of thrust modulation.

Mr. Sanders pointed out that trying to reduce thrust with a direct-drive constant-speed engine, by R.P.M. alone will necessitate contending with engine surge, poor engine specifics, poor acceleration characteristics, etc. He felt that variable pitch blading would be almost inevitable in this situation.

Mr. Hunter suggested the use of variable inlet stators in order to vary blade loading and therefore reduce thrust. Mr. Sanders recommended the report by Bell and DeKoster, for use in determining the effects of contravanes and for general fan design.

Mr. Sanders mentioned that he could foresee many difficulties in attempting to operate a turboprop engine over a wide power and R.P.M. range. He also wondered if the effects of side forces on the duct might be troublesome. Mr. Hunter mentioned that NACA has done quite a bit of work on side forces on engine cowls and rotating E-cowls. He did not mention any particular references on this work. At the conclusion of this discussion, Mr. Hunter arranged a meeting with Dr. Evvard and Mr. Cortright.

Conference with Dr. Evvard and Mr. Cortright

The main purpose of the conference with Dr. Evvard and Mr. Cortright was to discuss inlet and diffuser design. Both the ring vortex and boundary layer control methods of diffusion were discussed in detail. During this discussion, Mr. Cortright stated that either boundary layer control of trapped vortex diffusion might lead into trouble by pulling the flow off the center hub. Dr. Evvard also questioned the efficiency of a trapped vortex diffuser. He advised trying to diffuse over a longer length if possible.

During the discussion on inlet design, Dr. Evvard commented that no one knew the optimum inlet shape. Mr. Hunter stated that he was under the impression that Stack had found it difficult to persuade a fixed geometry shroud to behave well at high and low speeds. Both Dr. Evvard and Mr. Cortright agreed that the possibility of slotted inlet lips is feasible. Dr. Evvard commented that Moeckel had done some work on leading edge suction, and different lip radii, to be published as TN3457.

Visit to David Taylor Model Basin on July 13, 1955
to Discuss Ducted Propeller Tests

On July 13, 1955, Messrs. J. O'Malley, E. Sing and J. Zabinsky visited the David Taylor Model Basin to discuss the possibility of performing wind tunnel tests on ducted propellers. A meeting was held in the office of J.N. Fresh, Head of the Subsonic Flight Division. The conferees were:

J. N. Fresh	Head, Subsonic Division Aero Lab.	DTMB
W. Barnett	Head, Development Test Branch	DTMB
Dr. S. de los Santos	Head, Applied Research Branch	DTMB
Capt. W. G. Reid	Army Transportation Corps	ONR
J. Beebe	TCAVD - E & D	Army
R. H. Putnam	Office of Transportation Corps	Army
J. A. O'Malley	Project Aerodynamicist	Bell
J. M. Zabinsky	Aerodynamicist	Bell
E. Sing	Project Engineer Preliminary Design	Bell

The visits of Bell people to other facilities, and the information obtained was discussed. The complete lack of experimental data on ducted fans was pointed out. It was noted that such data had been desired since our first proposals and that such information would greatly assist our ducted fan transport study. Mr. Fresh agreed that the need for data existed and felt that his group could handle the work. They had done some work with small compressors for jet simulation and he was sure that the experience could be applied to the testing of ducted fans. He suggested that the majority of tests on different configurations could be made statically in their vertical non-flow tunnel. These tests would lead to the choice of a lesser number of configurations for testing through the range of flight speeds and angles of attack considered for the airplane.

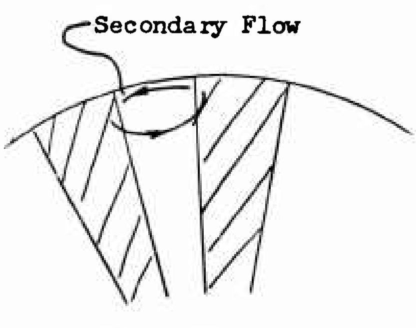
It was noted that the University of Wichita was interested in ducted propeller work and had been granted a contract which they might be able to redirect so as to concentrate on ducted propellers. It was felt that permission to redirect their present contract could be obtained, and that Dean K. Razak would like to do so. Subsequently the Office of Naval Research requested the University to redirect its effort under Contract No. Nonr-201(01) to support the Bell Aircraft study of a Ducted Propeller Transport. Although considerable interest existed at DTMB, no action was possible at this time.

<u>Visit to Kaman Aircraft
to Discuss Problems on Ducted Propellers</u>

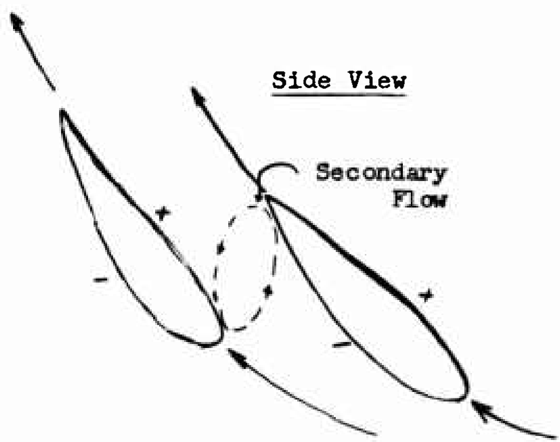
On August 9, 1955, Messrs. E. Sing and J. Zabinsky of Bell Aircraft visited the Kaman Aircraft facility at Bloomfield, Conn. to discuss ducted propellers and fans. The visit was made at the suggestion of Mr. A. Satin, Chief Engineer, Air Branch ONR since they have an ONR contract involving ring wing aircraft of the Coleopter type. The conferees from Kaman were:

Mr. J. Emerson - Chief Engineer
Mr. Arnold Kossar - Chief Analytical Engineer
Dr. Gabriel Isakson - Staff Engineer, Preliminary Design

Mr. Emerson left shortly after the conference started and the body of the discussion was with Mr. Kossar and Dr. Isakson. At the beginning Mr. Emerson apologized for the scant information he felt they had. They had subcontracted the Coleopter study work to Professor Raucher of the University of Zurich (formerly of M.I.T.) and had not yet received any reports from him. However, they have done some ducted fan design for cooling fan application for one of their helicopters and as a result had some interesting information. They found that for solidites of less than 75% the blade interference was only that of the vortex sheet and that the further multiblade interference was negligible. From NACA Lewis they learned, as a result of data not yet published, that some clearance at the tips was desirable on high solidity blading to relieve a secondary flow between blades which develops at zero clearance and which induces larger losses than the tip losses due to a small clearance. The size of the desired clearance had not been fully determined but it was felt that any design which did not have the outer ring fixed and rotating with the blades would of necessity have enough clearance to relieve these secondary flows. In the diagram below a plan view and end view of two adjacent blades is shown to illustrate the nature of this flow. This secondary flow occurs at the tip and is probably an effect of the constraint of the duct to any radial flow and pressure balance at the tip of the blades.



Front View



Side View

Conference at Hamilton Standard Division and UAC Research Division on Ducted Propeller Theory and Design

On August 10, 1955, E. Stevens, E. Sing and J. Zabinsky of Bell Aircraft, visited Hamilton Standard and the UAC Research Division to discuss theory design and fabrication of ducted propellers. The persons contacted are as follows:

Mr. Walt. Arnoldi, Hamilton Standard - Staff Engineer
Mr. Carl Rohrbach, Hamilton Standard - Ass't. Chief Aero.
Mr. John Fallon, Hamilton Standard - Aerodynamicist
Mr. Douglas Thatcher, Hamilton Standard - Sales Engineer

Mr. John W. North, UAC Res. Div. - Analysis Section.
Mr. Ted Edelbaum, UAC Res. Div. - Analysis Section.
Mr. Al. LeShane, UAC Res. Div. - Analysis Section.

Hamilton Standard Division

Mr. Walt. Arnoldi represented the management of the Propeller Division in the absence of the Chief Engineer, T. Rhines and the Chief of Aerodynamics, George Rosen.

The discussion was primarily with Mr. Rohrbach and Mr. Fallon. They reviewed our Aerodynamics blade design procedure and went over the prop. characteristics with no adverse comments. Mr. John Fallon is conducting a ducted propeller analysis. He reviewed our reference material and then described his work to date, the extent of which was rather meager. His analysis is based on the same general line of reasoning as portions of our analysis, but certain data which is used comes from the characteristics of known Hamilton Standard propellers. They had some preliminary curves of thrust to horse power (T/HP) as of function of horsepower to the diameter squared. One curve was for the ideal static thrust of a conventional propeller and the other was for an ideal shrouded propeller. A few checks were made to compare the curve with the one presented as Figure 1 in the first ducted fan progress report. The Hamilton Standard curve covered a pressure ratio range from 1.0 to 1.035. In this limited range the H.S. and Bell curves were essentially identical.

During the discussion with Mr. Rohrbach and Fallon they mentioned that blade thickness as low as 3% for activity factors from 150 to 200 were possible, but that they would recommend a minimum thickness of from 5% to 6% for a new application. These thicknesses were for all metal blades.

Mr. Arnoldi arranged a conference with personnel of the Research Department of UAC at East Hartford who had performed analyses of ducted propeller performance. At UAC we conferred with J. North, T. Edelbaum, and A. LeShane of the Analysis Section. After a short description of our activities the work of this group was reviewed. This consisted of an analysis which compared the thrust characteristics of shrouded and unshrouded propellers at various forward speeds. The results show appreciable gains at static conditions and a gradual fall off until there is no longer any net advantage at about 300 knots. From the basis of these results, the group at UAC Research had recommended that Hamilton Standard should support further work on this subject. They had not received any encouragement until the stimulus of our inquiries prompted the present investigations at the propeller division. The engineers that we spoke to felt that investigations of ducted propellers would be very worthwhile field of development.

Visit to the Forrestal Research Center of Princeton University on Ducted Propeller Problems

On September 8, 1955, R. Macey, E. Sing, and J. Zabinsky of Bell Aircraft visited the Forrestal Research Center of Princeton University to discuss ducted propeller theory and analysis. The Bell people conferred with the following Princeton personnel:

Prof. Courtland D. Perkins - Chairmain, Aero. Engr. Dept.
Prof. David C. Hazen - Aero. Engr. Dept.
Prof. A. A. Nikolsky - Aero. Engr. Dept.

The Bell personnel were received very cordially by Prof. Hazen who was joined by Prof. Nikolsky.

The progress and activities on the Ducted Propeller Transport Study were outlined. J. Zabinsky outlined the method that is used in the design of propellers and ducts. The methods of improving the unit characteristics were discussed and the University of Wichita program to improve diffuser efficiency was reviewed. Prof. Hazen felt that efforts to improve the characteristics would result in only small improvements in thrust. It was agreed that in the practical case, only simple devices such as a slotted duct trailing edge could be considered for present designs. The Ringlieb or cusp type diffuser was discussed and Hazen stated that the phenomenon was not completely understood and that the one successful model had been dismantled. He agreed with the University of Wichita tests which showed that excessive power was required to maintain the vortex in the cusp.

The joint Bell-University of Wichita wind tunnel investigations of the ducted propeller were described and Nikolsky stated that this program would provide the best possible type of information toward proving the ducted propeller system of propulsion.

A $50,000 contract has been awarded to Princeton by the ONR for testing the test bed configurations, using smoke visualization studies in a three-dimensional tunnel. The four configurations to be tested are, 1) Vectored slipstream, 2) Tilting wing, 3) Jet lift, and 4) Ducted propeller. As can be seen, two of the four could furnish data for Bell Aircraft projects.

Prof. Nikolsky showed considerable interest in the Bell Aircraft jet lift development programs and proposals. He stated that he liked our direct jet lift designs and thinks that there are great possibilities for this type of aircraft.

The concepts of STO and VTO aircraft were compared and it was agreed that generally an aircraft could be designed for STO with much less power than a pure VTO aircraft. Hazen and Nikolsky felt that people are not yet clear on this aspect of the problem and do not realize the cost in horsepower required.

Both of them were familiar with the work of Lippisch at Collins Radio, and advised us to arrange a visit to Collins so that we can get a first-hand picture of the activity there.

Conferences at the University of Wichita and at Collins Radio, Cedar Rapids, Iowa

On October 12 Messrs. Sing, O'Mally, and Zabinsky of Bell Aircraft visited the University of Wichita to discuss the ducted propeller wind tunnel program which was being prepared to support the Bell studies. The discussions were held with Dean K. Razak, Mr. M. Snyder, head of the Aeronautical Engineering Department and members of the staff. The model design data had been received. The test program was discussed in some detail. It was decided that pressure and force measurements would be taken; that two or three models would be tested covering a range of propeller pressure ratios, duct geometry, and blade loadings. A tentative schedule for the tests was set, so as to try to have some of the data available before the end of the study contract. Liaison with the University will be maintained.

On October 13, 1955 the above mentioned Bell personnel visited Dr. Lippisch of Collins Radio, Cedar Rapids, Iowa to discuss ducted propellers. Dr. Lippisch explained his theories and showed movies of his models. He basically has developed a perfect fluid analogy describing the action of the duct in increasing thrust. He said that the flow downstream of the duct may be represented by a cylindrical vortex sheet which adds flow to the jet stream of the propeller. He uses cascade methods to design the shrouded propellers. His concept of the aerodyne is a wingless vehicle supported and propelled by the propeller. As forward speed increases the thrust increases allowing both vertical and horizontal forces to be balanced. He also described generally some force data on the ducts at angle of attack. He said that the forces on a ring wing and a ducted propeller are entirely different. At the conclusion of the meeting, Dr. Lippisch showed the movies of his models. They were both interesting and informative.

Search at ASTIA Document Service Center,
Dayton, Ohio

During the period from November 7 - 9, 1955 Mrs. Jasmine H. Mulcahey, Chief Librarian, Bell Aircraft Corporation, visited the ASTIA Document Service Center at Dayton, Ohio for the purpose of conducting a search for material pertinent to ducted propellers. A number of reports were ordered for later screening. Mrs. Mulcahey reported that the attitude at the center was both cordial and cooperative and that an exhaustive search was made with a minimum of difficulty.

Discussion of Ducted Fans
With the Personnel of the Cascade
Aerodynamics Section of the NACA, Langley Field, Va.

On February 9, 1956, Messrs. L. Landphair, J. O'Malley, E. Y. Sing and J. Zabinsky visited the NACA installation at Langley Field, Va. to confer with the personnel of the Cascade Aerodynamics Section. In the morning, Mr. Emanuel Boxer, head of the supersonic cascade group and Mr. James Dunavant, were contacted for discussions on cascade design. In the afternoon, Mr. J. Erwin, Head of the Cascade Aerodynamics Branch and Mr. Westphal joined the discussion.

Cascade Conference

We explained our approach to the ducted fan design and pointed out our need for cascade data in the solidity range below 0.5 and in the inlet angle range below 30°. Mr. Boxer said that no test work had been done in this range. The extrapolated data that had been used was shown and both Messr. Boxer and Dunavant agreed that the method of extrapolation and the results appeared reasonable. They asked if we could send them copies of the curves.

A discussion of the fan design using inlet guide vanes led to some pertinent comments on inlet guide vane design. Mr. Dunavant recommended that inlet guide vanes have a solidity at the tip of about 1.0 and that we taper the blades to get this if necessary. They pointed out that our assumption of ±20° angle of attack variation on the inlet guide vanes was probably a little conservative since in their experience an uncambered airfoil will have about as large an operating angle of attack range as a moderately cambered airfoil. This latter comment was in reference to our use of the inlet guide vane data of RM L54I02 which showed a linear angle of attack range to 24 and 28 degrees for inlet guide vanes of moderate camber.

On one of their inlet compressor stage models they had used a large prewhirl angle to obtain high velocities over the blade. They found from this that they could get good control over rotor performance with relatively small inlet guide vane angle variation. They suggested that such a design might simplify our problems of inlet guide vane angle variation over the velocity and altitude range. Such a design would be more sensitive to Mach number effects since the use of prewhirl will increase the relative velocity over the blades.

Questions were asked concerning maximum angle of attack, blade choking and duct choking. Mr. Boxer said that our designs, if we maintained subsonic relative Mach numbers at the blades, would experience no choking problem. The use of twice minimum drag as defining stall angle of attack was completely arbitrary, and was taken for convenience from the early British work. This method gives a fair estimate for the beginning of a design but they said a check of the stall angle should be made once the section was chosen. They reitterated that blade choking was very unlikely in our design. They said that the possibility of the fan inducing sonic axial velocity could be disregarded since under these conditions the flow would be metered by the leading edge shock waves on the blades.

We asked their opinion of the inlet flap design on the fan design #1. This was the practical flap which would attempt to approximate a bell mouth. They said that as long as we maintained a favorable pressure gradient some radius at the hinge line would probably not be critical. They warned against reverse curvature since this leads to unfavorable pressure gradient and separation. This would have drastic effects. They did not have any information on the effect of the gaps but agreed that they could be very small.

The problem of turbining at the blade tips under some reduced power conditions was discussed. They had tested some fans which had these characteristics and had found that the overall efficiency was reduced only slightly even though the efficiency of the turbining portion of the blades would calculate as negative.

They said that the radial distribution of axial velocity was a function of the radial blade loading, and recommend TN2598 by Savage. The use of a free vortex tangential velocity distribution is used because this gives a constant axial velocity with radius. In calculating a multistage compressor use of some other distribution would require calculation of the axial velocity variation with its probable error. In a 10 or 11 stage fan, the design of the final stages would be extremely doubtful due to this accumulation of error. They did say that use of a forced vortex would allow higher pressure ratios per stage and would allow a reduction in number of stages for a given overall pressure rise.

Our design method takes advantage of both these factors. By designing a free vortex at an advanced flight speed where the pressure ratio is low; the fan in adjusting to static operation, either by pitch change or inlet guide vane rotation, approaches a forced vortex distribution for this higher pressure ratio condition. This results in the need for a minimum of rotor control through either pitch change or guide vane rotation.

They mentioned that rotor relative speeds approaching M = .95 were not prohibitive. In fact, they had observed a slight rise in efficiency from M = .8 to M = .95 before the drop off due to a close approach to sonic velocity.

In talking about the wind tunnel tests at the University of Wichita, they have found that Reynolds number effects can be ignored if the Reynolds number based on blade tip chord was greater then 100,000. They are interested in getting any compressor or rotor data which may be forthcoming from the Wichita tests. They would only be interested in parameters common to compressor terminology. In general, we do not anticipate measuring such items.

After lunch, Mr. John Erwin, head of the Cascade Aerodynamics Branch and Mr. Westphall, who were unavailable in the morning joined the discussion. They stressed the use of prewhirl in the inlet guide vanes to minimize the inlet guide vane variation necessary for rotor angle of attack control. They suggested such things as flap on the guide vanes to replace incidence variation or a blowing jet out of an elliptical guide vane. These ideas were mentioned in passing with the realization that a study of them would be involved and might show these methods to be unfeasible.

Some of the numbers which they had available from their high prewhirl fan are listed below.

at 1900 RPM

Axial velocity = 508 ft/sec
Rotor angle of attack tip 9.9°
Root 12.8° Pressure Ratio 1.05

Axial velocity = 231 ft/sec
Rotor angle of attack tip 18.2°
Root 20.4° Pressure Ratio 1.075

The fan had 60° of prewhirl at the root and 45° at the tip. The hub to tip diameter ratio was 14.5/21 = .69.

Mr. erwin mentioned that the design angles of attack shown in the low speed cascade data increased from 3 to 6 degrees at relative Mach number of .84 and greater; 6° for high camber and low inlet angle and 3 degrees for low camber and high inlet angle.

We showed our extrapolation of the cascade data to Messrs. Erwin and Westphall. They also requested copies. Mr. Erwin called in Mr. Cliff Emery and asked what the possibilities were of running a few points in the cascade tunnel to check our data. Mr. Emery said that he was just finishing a series of runs and he could easily check a few points in the morning. Mr. Erwin said he'd send us this data as soon as it was available.

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